

Probing color reconnection with underlying event observables at the LHC energies

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In this work, we study the underlying-event (UE) activity as a function of the highest jet or charged-particle transverse momentum (p_T^{jet} or p_T^{leading}) in terms of number and summed- p_T densities of charged particles in the azimuthal region transverse to the leading jet or particle direction. Contrary to inelastic pp LHC data, the UE observables normalized to the charged-particle density obey an approximate Koba-Nielsen-Olesen (KNO) scaling. Based on PYTHIA 8.2 simulations of pp collisions at LHC energies, we show that the small breaking of the KNO scaling is due to the increasing importance of multiple partonic interactions (MPI) at higher \sqrt{s} . This in turn makes that with increasing energy, the p_T spectra in the UE get harder than in inelastic pp collisions. Color reconnection (CR) models the interactions among outgoing partons just before the hadronization; therefore, it modifies the p_T -spectral shape. Motivated by this, we studied the UE activity considering charged particles within different p_T intervals in pp collisions at $\sqrt{s} = 7$ TeV. Although MPI saturate for $p_T^{\text{jet}} > 10$ GeV/ c , the UE still increases with increasing p_T^{jet} . We demonstrate that the saturation of both number and summed- p_T densities, which are commonly claimed, are only observed for low- p_T charged particles ($0.5 < p_T < 2$ GeV/ c). Moreover, for the p_T -integrated case ($p_T > 0.5$ GeV/ c), the summed- p_T density is not sensitive to the variation of CR; however, at low- p_T , it is reduced with increasing CR, whereas an opposite behavior is found at intermediate p_T ($2 < p_T < 10$ GeV/ c). Finally, we show that CR produces flowlike behavior only in the UE region, and the effects are reduced with increasing p_T^{jet} due to the hardening of UE. The outcomes encourage the measurement of inclusive and identified charged-particle p_T spectra (over a wide range of p_T) associated to UE aimed at better understanding the similarities between pp and heavy-ion data discovered at the LHC.

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I. INTRODUCTION

In the context of event generators, one single inelastic (nondiffractive) proton-proton (pp) collision can be split into two components: the main hard partonic scattering and the underlying event (UE). The latter includes initial- and final-state radiation (ISR/FSR), multiple partonic interactions (MPI), and the fragmentation of beam remnants resulting from the hadronization of the partonic constituents that did not participate in any scatter. On top of that, color

reconnection (CR) is a microscopic mechanism that describes the interactions that can occur between color fields during the hadronization transition. It is a key ingredient which is needed to explain the increase of the average transverse momentum as a function of charged-particle multiplicity [1] and the multiplicity-dependent event shape studies [2]. The importance of the UE relies on the fact that it can shed light in the search for new physics phenomena at hadron colliders [3] or even in the quest for precise Standard Model measurements [4].

The UE observables have been measured in $p\bar{p}$ collisions in dijet and Drell-Yan processes at CDF at $\sqrt{s} = 1.8$ and 1.96 TeV [5,6]. At the start of the LHC most of the existing Monte Carlo models were tuned using Tevatron data. In this sense, early measurements provided by the ATLAS experiment [7] showed clear differences between event generators and data. Latest results have shown an

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improvement on the description of the UE by the new Monte Carlo tunes [8]. However, we should keep in mind that the modeling of UE is more challenging than traditionally assumed because recent results suggest the unexpected presence of heavy ionlike behavior in pp data [9–12]. We should therefore go beyond the traditional UE analysis for better understanding the similarities between pp and heavy-ion data.

In order to understand the physics behind high-multiplicity pp collisions, we have performed several studies using the PYTHIA 8 [13] event generator. We have found that CR together with MPI can produce radial flow patterns via boosted color strings [14]. The analysis as a function of event multiplicity allows us to study events with different amount of MPI; however, we have shown that high-multiplicity pp collisions are effected by the so-called fragmentation bias [15,16]. Moreover, for a fixed amount of MPI, CR strongly modifies the charged-particle multiplicity; therefore, a selection based on multiplicity does not permit the isolation of CR effects in events with the same MPI activity. In this work, we propose to exploit the usage of UE in order to increase the sensitivity to events with multiple semihard scatterings instead to biased fragmentation of high transverse momentum jets. Similar ideas have been proposed in order to disentangle autocorrelation effects from other physical phenomena by measuring the charged-particle multiplicity in the UE region [17].

Given that heavy-ion data feature remarkable differences between the particle production associated to bulk (everything outside the jet peaks) and jets [18,19], we have decided to perform an analogous analysis in pp collisions simulated with PYTHIA 8. The advantage is that cutting on the highest charged-particle transverse momentum (p_T^{leading}) or highest jet p_T (p_T^{jet}) it is possible to select events with larger (and nearly constant) MPI activity than that associated to inelastic events. This allows us to enhance color-reconnection effects on the hadronization.

Specifically, in this paper, we study the modification of the traditional UE observables when charged particles within different p_T intervals are considered. We also aim to understand how the underlying-event activity is affected when either p_T^{jet} or \sqrt{s} are varied. The analysis is not restricted to the traditional average quantities; instead, we study the p_T spectra of unidentified and identified charged particles within UE environments modified with a selection on p_T^{jet} . The measurements of the p_T spectra sensitive to UE as a function of p_T^{jet} are proposed as a tool to probe the QCD Monte Carlo picture using LHC data.

The article is organized as follows: Sec. II provides information about the event and particle selection for the simulations, Sec. III discusses the energy dependence of the UE in terms of the number and summed- p_T densities,

Sec. IV presents the results on how CR affects the UE observables and the p_T distribution of identified charged particles, and finally, Sec. V contains the summary and outlook.

II. SIMULATIONS AND ANALYSIS

Quantities sensitive to the UE are constructed as follows. The perpendicular plane to the beam axis is segmented into three regions depending on the azimuthal angular difference ($\Delta\phi$) relative to the leading object (e.g., jet or charged particle) axis. Unless specified, those particles with $\pi/3 < |\Delta\phi| < 2\pi/3$ (transverse side) are the only ones used for the present analysis since they are the most sensitive to UE. The underlying-event observables are defined as the mean number of charged particles per pseudorapidity unit and per azimuthal separation unit ($\langle N_{\text{ch}}/\Delta\eta\Delta\phi \rangle$) and the mean scalar sum of transverse momentum per pseudorapidity unit and per azimuthal separation unit ($\langle \Sigma p_T/\Delta\eta\Delta\phi \rangle$). Hereafter, $\langle N_{\text{ch}}/\Delta\eta\Delta\phi \rangle$ and $\langle \Sigma p_T/\Delta\eta\Delta\phi \rangle$ are referred to as number density and summed- p_T density, respectively. PYTHIA 8.212 [13] tune Monash 2013 [20], hereafter referred to as PYTHIA 8, was used to simulate inelastic pp collisions at the LHC energies. Since simulations are intended to be compared to CMS [21], ATLAS [8], and ALICE [22] results available on HEPData [23], different selections at particle and event levels were implemented:

- (1) The comparison of simulations with CMS data (pp collisions at $\sqrt{s} = 0.9$ and 7 TeV) requires a leading jet with transverse momentum larger than 1 GeV/ c within the pseudorapidity interval: $|\eta| < 2$. Jets are defined using the SIScone algorithm [24] as implemented in FastJet 3.3 [25] with the clustering radius given as $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.5$. Furthermore, jets are built using charged particles with $p_T > 0.5$ GeV/ c and $|\eta| < 2.5$. The UE observables are computed using charged particles within $|\eta| < 2$ and $p_T > 0.5$ GeV/ c . Notice the η range of particles used to build the jets is larger than that of particles in the UE in order to avoid a kinematic bias.
- (2) The comparison with ALICE data (pp collisions at $\sqrt{s} = 0.9$ and 7 TeV) requires charged particles with $p_T > 0.5$ GeV/ c and $|\eta| < 0.8$ with the transverse momentum of the leading charged particle above 0.5 GeV/ c .
- (3) The comparison with ATLAS data (pp collisions at $\sqrt{s} = 13$ TeV) requires charged particles with $p_T > 0.5$ GeV/ c and $|\eta| < 2.5$ with the transverse momentum of the leading charged particle above 1 GeV/ c .

In all cases, the configuration used in PYTHIA 8 was the following: Beams:idA = 2212, Beams:idB = 2212, Beams:eCM = 900 (7000 and 13000), Tune:pp = 14, and SoftQCD:inelastic = on.

III. ENERGY DEPENDENCE OF THE UNDERLYING EVENT

In a previous publication [26], we have shown that within 10% the UE observables as a function of p_T^{leading} collapse on \sqrt{s} -independent curves once they are scaled to the corresponding average charged-particle density ($dN_{\text{ch}}/d\eta^{\text{inelastic}}$). This quantity is obtained for inelastic pp collisions at a given center-of-mass energy. In this paper, we want to trace back the origin of the small imperfection of the scaling behavior, i.e., its validity within 10%. Instead of using ATLAS UE data (measured as a function of p_T^{leading}), now we use the CMS data since they are reported for a wide p_T^{jet} interval. This allows us the study of pp events with exceptional high- p_T jets. In order to obtain the charged-particle density, the transverse momentum distributions of charged particles in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV [27,28] were integrated for $|\eta| < 2.4$ and $p_T > 0.5$ GeV/c. The total uncertainties (quadratic sum of statistical and systematic uncertainties) associated to the p_T spectrum were propagated to the integral and assigned as systematic uncertainty to $\langle dN_{\text{ch}}/d\eta \rangle^{\text{inelastic}}$. For pp collisions at $\sqrt{s} = 0.9$ and 7 TeV, the computed values were $\langle dN_{\text{ch}}/d\eta \rangle^{\text{inelastic}} = 1.20 \pm 0.04$ and 2.33 ± 0.11 , respectively. Therefore, the relative variation (f) of the average charged-particle density in pp collisions at $\sqrt{s} = 7$ TeV with respect to pp collisions at $\sqrt{s} = 0.9$ TeV was found to be $f = 1.94 \pm 0.11$.

Figure 1 shows the number (left panel) and the summed- p_T (right panel) densities as a function of p_T^{jet} after scaling by a $1/f$ factor. Little or no energy dependence is observed after the implementation of the scaling factor. This is what we called “universality of UE” in our previous work where p_T^{leading} was used instead [26]. The results are compared with PYTHIA 8 simulations since it reproduces very well many features of LHC data. We observe that the scaling

properties hold up to $p_T^{\text{jet}} = 25$ GeV/c. Regarding the behavior of data, a steep rise of the underlying activity with increasing p_T^{jet} is observed. This fast rise is followed by a change of the slope above $p_T^{\text{jet}} \sim 10$ GeV/c. The change of the slope is understood as due to very small impact parameter pp collisions which yields to a saturation of the MPI activity. Different publications state that above 10 GeV/c the UE observables saturate, reaching nearly constant values [8,22,30]. However, we want to stress the fact that both data and PYTHIA 8 still show a rise of the UE activity with increasing p_T^{jet} . In the next sections, we discuss how color reconnection contributes to that behavior.

The universality of UE can be interpreted as the approximate Koba-Nielsen-Olesen (KNO) [31] scaling of the particle production associated to the UE. For this reason, we studied the energy dependence of the KNO variable: number density in the transverse side normalized to the charged-particle density (inelastic pp collisions). This ratio has been studied by ALICE using pp data at $\sqrt{s} = 0.9$ and 7 TeV [22]. To obtain the numerator, ALICE fitted a first degree polynomial to the number density as a function of p_T^{leading} for $p_T^{\text{leading}} > 5$ GeV/c. Within uncertainties, the fit slope was found to be consistent with zero and the constant parameter was identified as the average number density in the transverse side. Potential correlations of the systematic uncertainties in different p_T bins were neglected. The left-hand side of Fig. 2 shows a comparison of the KNO variable as a function of $\log(\sqrt{s})$ measured by ALICE and ATLAS. ALICE data points were taken from [22] while the ATLAS point was derived following the strategy already described. PYTHIA 8 inelastic pp events were simulated in order to test the scaling of UE over the wide \sqrt{s} interval covered at the LHC. Going from pp collisions at $\sqrt{s} = 0.9$ to 13 TeV, PYTHIA 8 simulations show a $\sim 8\%$

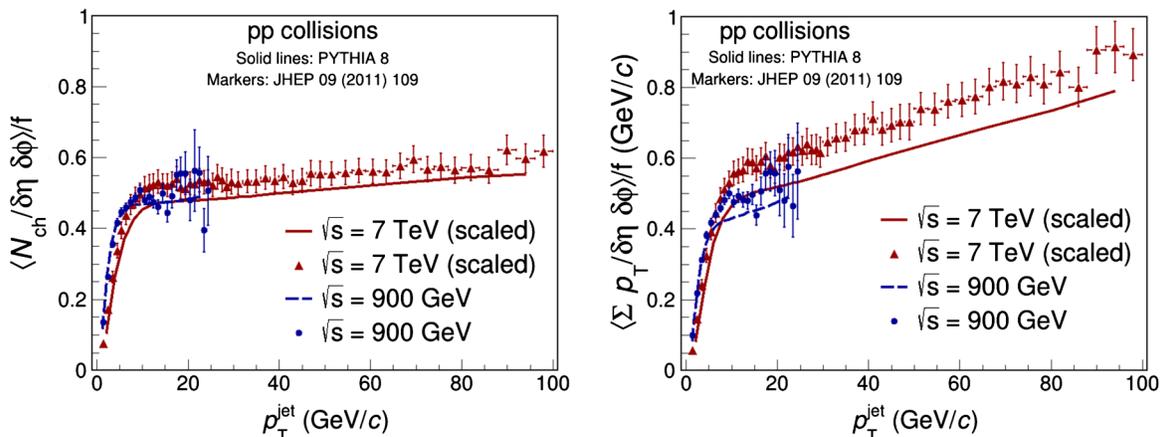


FIG. 1. The number density (left) and the summed- p_T density (right) as a function of p_T^{jet} in the UE region. A factor f that takes into account the relative charged-particle density increase from 0.9 to 7 TeV has been applied. Data are shown as markers, and the error bars represent the total uncertainties (the one measured by CMS and the associated to f). Solid lines are the results obtained with PYTHIA 8.

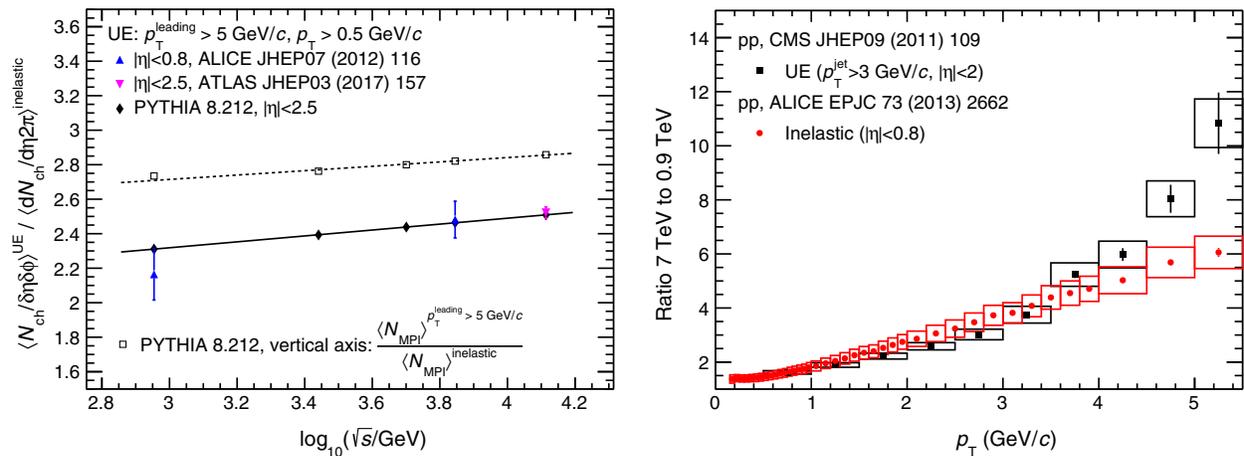


FIG. 2. Left: Energy dependence of the number density (UE) normalized to the average charged-particle density in inelastic events. PYTHIA 8 simulations of pp collisions at $\sqrt{s} = 0.9, 2.76, 5.02, 7,$ and 13 TeV (full black markers) are compared to ALICE (full blue markers) and ATLAS data (full magenta markers). Similar ratios (empty markers) were obtained using the number of multiple partonic interactions (N_{MPI}). Right: UE transverse momentum distribution (associated to $p_T^{\text{jet}} > 3$ GeV/c) in pp collisions at 7 TeV normalized to the corresponding one at 0.9 TeV (black squares). Results are compared to analogous ratios for inelastic pp collisions at the same energies (red circles). Statistical and systematic uncertainties are represented as error bars and boxes around the data points, respectively. Data were obtained from [21,29].

increase of the KNO variable. Within uncertainties, the data exhibit the same trend. The small \sqrt{s} dependence is also observed if we consider the average number of MPI in events with $p_T^{\text{leading}} > 5$ GeV/c (central pp collisions) normalized to this same observable but in inelastic pp collisions (i.e., without any selection on p_T^{leading}). The ratio as a function of $\log(\sqrt{s})$ is described by a first degree polynomial with a slope parameter of 0.13, which is close to what is obtained using the number density (slope 0.17), suggesting a common origin.

In order to investigate the features of particle production associated to UE, in particular the excess of particles in UE with respect to inelastic pp collisions, we studied the p_T spectra of unidentified charged particles. The CMS Collaboration has reported such spectra for pp collisions at $\sqrt{s} = 0.9$ and 7 TeV. The UE corresponds to events with $p_T^{\text{jet}} > 3$ GeV/c within $|\eta| < 2$. To study the evolution of the p_T -differential particle production with increasing energy, the 7 TeV p_T spectrum was normalized to the corresponding one at 0.9 TeV. The results are presented in the right-hand side of Fig. 2. An analogous ratio as a function of p_T was obtained using the p_T spectra of inelastic pp collisions at the same energies [29]. Within uncertainties, both ratios are consistent up to $p_T = 4$ GeV/c. For higher p_T , the ratio increases faster for the UE activity than for inelastic pp collisions. The results suggest that, with increasing \sqrt{s} , intermediate- p_T particle production increases faster in the UE than in inelastic pp collisions. This effect could explain the faster rise of the number density in the UE relative to the corresponding inelastic events [22]. Transverse momentum

distributions sensitive to UE for other \sqrt{s} and p_T^{jet} are needed in order to confirm the validity of this conclusion.

IV. CR STUDIES USING UE OBSERVABLES

We have shown that, with increasing \sqrt{s} , the p_T spectra sensitive to UE get harder than that in inelastic events as a consequence of the \sqrt{s} dependence of MPI. Since in events with a large number of MPI color reconnection modifies the particle production [14], CR effects on UE are expected. In order to quantify such effects, we used the default CR model of PYTHIA 8 (MPI based). The model includes the reconnection probability (rr) to join low and high p_T partons. Therefore, rr (ColourReconnection:range in PYTHIA 8) allows us to control the amount of interactions which partons feel just before the hadronization. For our study, we computed $\langle N_{\text{ch}} / \Delta\eta\Delta\phi \rangle$ and $\langle \Sigma p_T / \Delta\eta\Delta\phi \rangle$ in three different p_T ranges depending on the transverse momentum of the charged particles present in the UE: integrated ($p_T > 0.5$ GeV/c), low ($0.5 < p_T < 2$ GeV/c), and intermediate ($2 < p_T < 10$ GeV/c) transverse momentum. Each p_T -dependent UE quantity was in turn computed for three different values of rr : 0, 1.8, and 10, corresponding to the minimum, nominal (tuned to LHC data [20]), and maximum possible values in PYTHIA 8. Moreover, the results presented here are obtained using leading jets within the CMS kinematic ranges, allowing us the comparison between data and PYTHIA 8 over a broad p_T^{jet} interval. Since we claim an approximate scaling of the particle production associated to UE, we report results only for pp collisions at $\sqrt{s} = 7$ TeV. The conclusions should hold for other energies.

A. Modification of the particle production at low and intermediate p_T

Figure 3 shows the number density as a function of p_T^{jet} for pp collisions at $\sqrt{s} = 7$ TeV. For the p_T -integrated case, CMS data are compared with PYTHIA 8 simulations considering three different values of rr . Within uncertainties, data are well described by simulations with $rr \geq 1.8$. As expected, the number density decreases with increasing rr due to the reduction of the number of color strings that connect the outgoing partons. Though, the p_T^{jet} dependence of the number density is the same for the different rr values. For the low- p_T case, we observe the same rr ordering reported for the p_T -integrated case. However, the number density is reduced by $\sim 20\%$ relative to the p_T -integrated case. The number density associated to intermediate- p_T particles exhibits an opposite trend with increasing rr ; i.e., going from low- to high- rr values, the number density increases suggesting a hardening of UE with increasing rr .

The corresponding plots for the summed- p_T density are shown in Fig. 4. Contrary to the number density, this observable presents a steeper rise with increasing p_T^{jet} and no color-reconnection effects are visible for the p_T -integrated case. However, this does not happen when the summed- p_T density is calculated considering low- or intermediate- p_T charged particles. Namely, for low- p_T particles, the summed- p_T density shows a saturation for $p_T^{\text{jet}} > 10$ GeV/c. Moreover, the summed- p_T density decreases with increasing values of rr (the CR

effect amounts to 5%). For the intermediate- p_T case, the summed- p_T density rises with increasing p_T^{jet} more or less at the same rate that the p_T -integrated case.

In order to avoid any possible jet effect (at small values of $|\Delta\eta|$) that could bias the previous results, an extra cut on $|\Delta\eta| > 1.6$ was tested. In this sense, only particles with $|\Delta\eta| > 1.6$ were selected, but no significant differences were observed.

In short, the behavior of the number density as a function of p_T^{jet} is determined by low-momenta particles while for summed- p_T , density is determined by intermediate- p_T particles. It was verified that, qualitatively, the same behavior is obtained for both UE observables at $\sqrt{s} = 900$ GeV. It is worth mentioning that UE measurements considering different p_T intervals are not available. Our work suggests the necessity of such measurements in order to test the picture of PYTHIA 8, i.e. the hardening of the UE structure with increasing p_T^{jet} (or \sqrt{s}) by means of MPI and CR.

B. Flowlike effects within a hard UE environment

It has been shown that CR produces flowlike effects that increase with increasing $\langle N_{\text{MPI}} \rangle$ [14]. This is because the number of strings connecting scattered partons naturally increases with increasing $\langle N_{\text{MPI}} \rangle$. CR allows the color fields of the event to be redirected, relative to the case of color-separated MPI, in such a way that the total string length is reduced. This produces a transverse boost to reconnected string pieces, that, e.g., provides to heavier hadrons higher

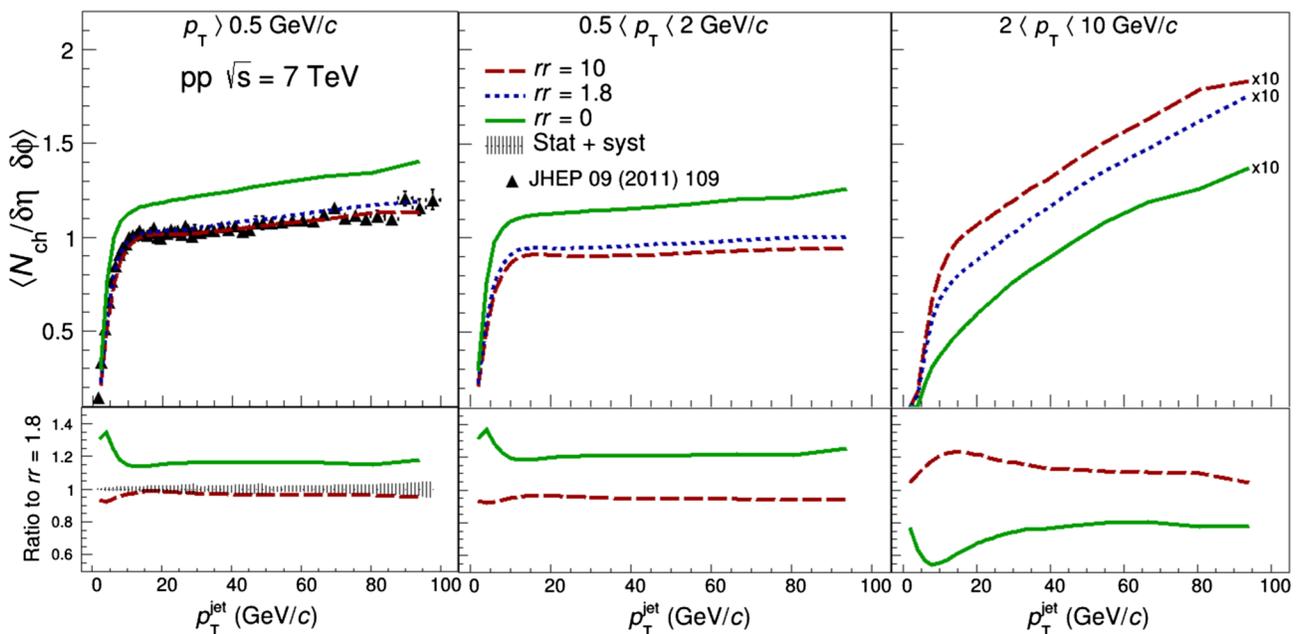


FIG. 3. The number density as a function of the p_T^{jet} for three different values of reconnection range. Results for the p_T -integrated case are displayed for both the CMS data and PYTHIA 8 simulations (left). Analogous results are shown for low- (middle) and intermediate- (right) p_T particles. Bottom panels show the variation of the number density with respect to $rr = 1.8$. Shaded areas around unity indicate the statistical and systematic uncertainty (added in quadrature) on CMS data.

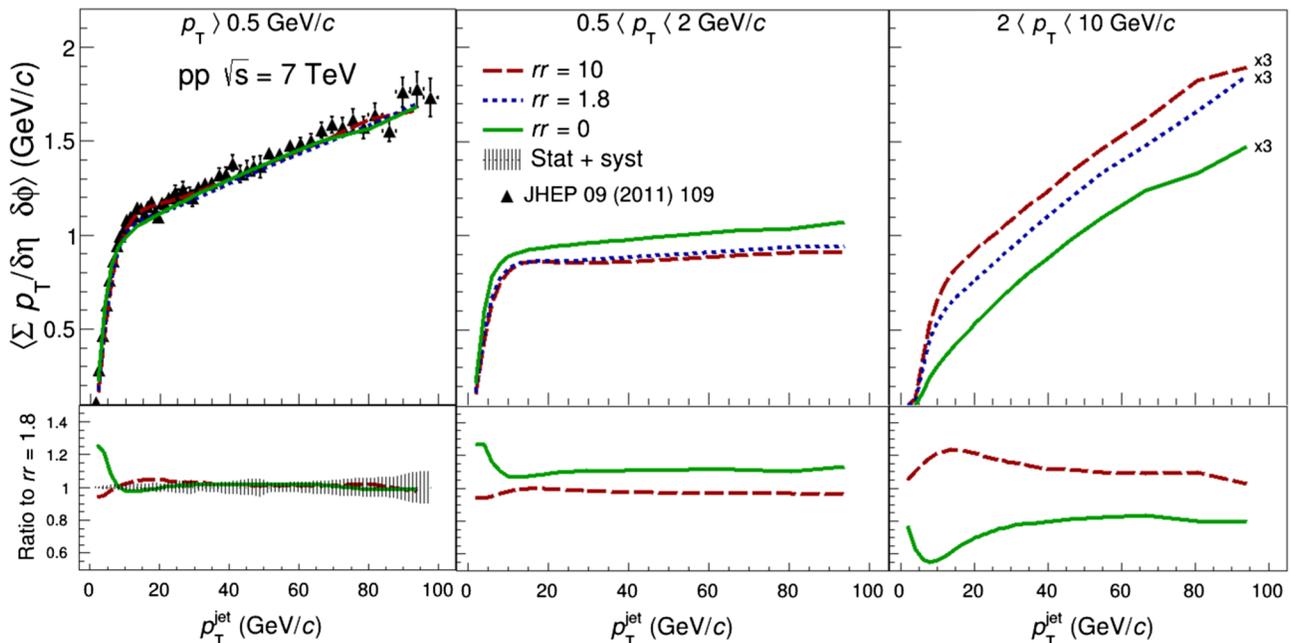


FIG. 4. The summed- p_T density as a function of the p_T^{jet} for three different values of reconnection range. Results for the p_T -integrated case are displayed for both the CMS data and PYTHIA 8 simulations (left). Analogous results are shown for low- (middle) and intermediate- (right) p_T particles. Bottom panels show the variation of the summed- p_T density with respect to $rr = 1.8$. Shaded areas around unity indicate the statistical and systematic uncertainty (added in quadrature) on CMS data.

$\langle p_T \rangle$ [32]. It has been shown that in events with enhanced UE activity, relative to inelastic pp collisions, the flowlike effects increase. This has been achieved by selecting highly spherical events where no jet structure is present [33]. Motivated by the similarity of the event-shape selection results with those for heavy-ion collisions where the proton-to-pion ratio (sensitive to radial flow [34]) is studied for the regions sensitive to bulk production and jet fragmentation, separately. We decided to perform an analogous Monte Carlo analysis but considering the underlying event accompanying a very high- p_T jet. The goal of the study is to understand how the p_T^{jet} selection affects observables sensitive to radial flow in the UE region.

Figure 5 shows the proton-to-pion ratio as a function of the hadron transverse momentum in the underlying-event region for two p_T^{jet} bins and for three different values of rr : 0, 1.8, and 10. The left-hand side of Fig. 5 shows the results for $30 < p_T^{\text{jet}} < 40 \text{ GeV}/c$. Going from independent fragmentation ($rr = 0$) to the largest value of rr , the proton yield is suppressed with respect to the pion one for $p_T < 2 \text{ GeV}/c$, whereas for intermediate transverse momentum the proton yield is enhanced relative to the pions. This is the mass effect attributed to color reconnection that was previously reported for the inclusive event [14], i.e., without any separation of the soft and hard components. It is worth noting that the size of the bump shown in Fig. 5 is smaller than that seen in the inclusive case [14]. The reduction is understood in terms of the hardness of the

underlying event that increases with increasing p_T^{jet} . The right-hand side of Fig. 5 shows the results when we move from $30 < p_T^{\text{jet}} < 40 \text{ GeV}/c$ to higher jet transverse momentum ($40 < p_T^{\text{jet}} < 100 \text{ GeV}/c$). Going from low- to high- p_T^{jet} values, the structure at $p_T = 3 \text{ GeV}/c$ is reduced. Moreover, the results show a smaller dependence on rr indicating that the ratio is more sensitive to the fragmentation of hard partons.

Finally, in order to show the distinct behavior of the UE with respect to jet fragmentation, Fig. 6 presents the proton-to-pion ratio as a function of p_T obtained for the towards region ($|\Delta\phi| < \pi/3$). In particular, only pions and protons within $R < 0.5$ are considered. Notice that, opposite to Figs. 3 and 4, the ratios in the bottom panels of Figs. 5 and 6 are performed relative to $rr = 0$. The reason is because in the latter case the goal is to quantify the flowlike effect, if any, that is observed when color reconnection is present.

Overall in Fig. 6, the ratio is significantly smaller than the corresponding for the underlying-event region. For example, while for the transverse region the ratio shows a maximum amounting to ~ 0.22 at $p_T = 3 \text{ GeV}/c$; for the jet peak ($30 < p_T^{\text{jet}} < 40 \text{ GeV}/c$), it reaches 0.1 and the value is subsequently reduced with increasing p_T^{jet} . It is worth mentioning that although a color-reconnection effect is observed in the jet region as a consequence of the UE contamination, its effect is smaller than what is seen in

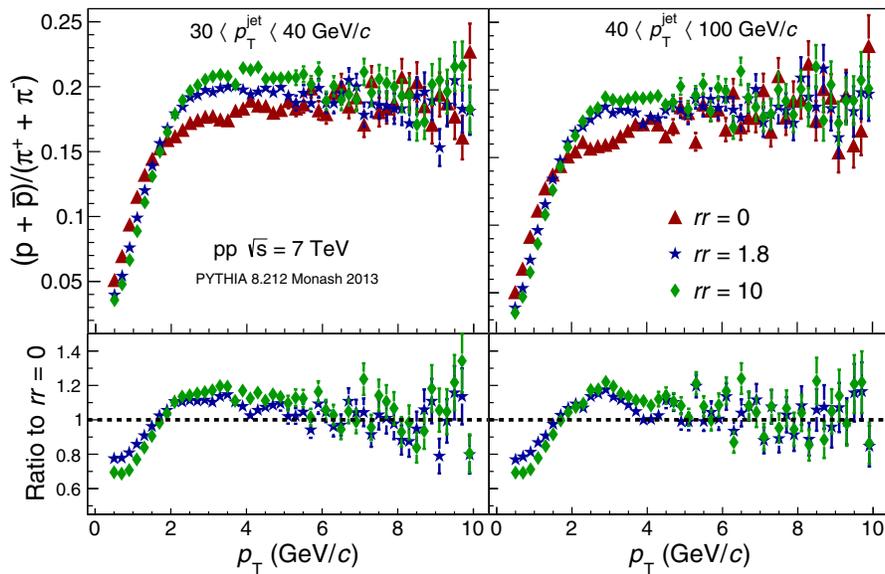


FIG. 5. Proton-to-pion ratio in the UE as a function of the hadron transverse momentum for different values of reconnection range in two p_T^{jet} intervals: 30–40 GeV/c (left) and 40–100 GeV/c (right). Bottom panels show the variation of the proton-to-pion ratio with respect to $rr = 0$. Error bars indicate the statistical uncertainties.

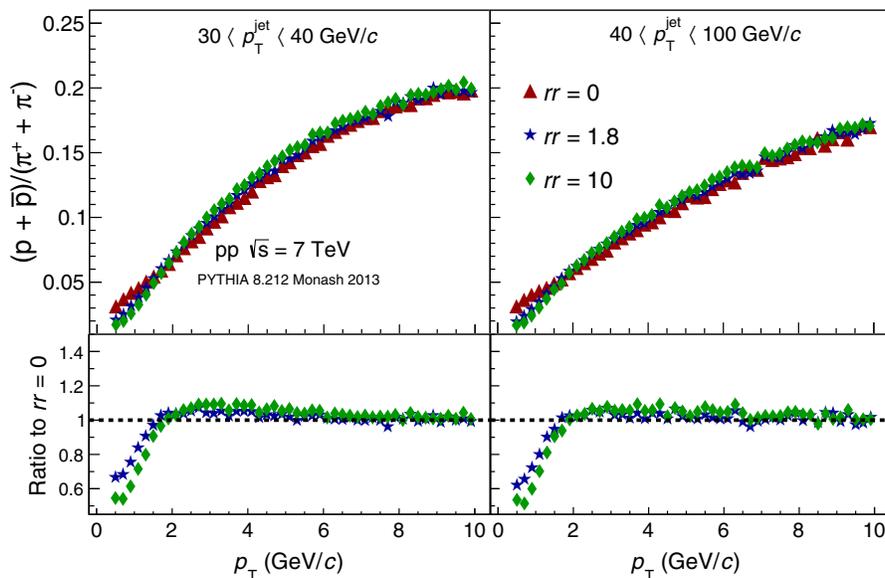


FIG. 6. Proton-to-pion ratio in the jet region and within $R < 0.5$ as a function of the hadron transverse momentum for different values of reconnection range in two p_T^{jet} intervals: 30–40 GeV/c (left) and 40–100 GeV/c (right). Bottom panels show the variation of the proton-to-pion ratio with respect to $rr = 0$. Error bars indicate the statistical uncertainties.

the transverse side. The effects observed for the UE and jet regions are qualitatively similar to those measured in heavy-ion collisions resulting from the jet-bulk separation using leading-hadron correlations. The statement there [18] is that the flowlike peak observed in proton-to-pion ratio for the most central Pb-Pb collisions at the LHC energies is a medium effect.

The effects reported in this paper should be searched in data; the outcome would contribute to the understanding

of the unexpected heavy ionlike signals discovered in small systems by LHC experiments [11,12,35].

V. CONCLUSIONS

Motivated by the results of our previous work [26], where we shown that the particle production sensitive to the underlying event (UE observables) exhibited an approximate KNO scaling. In this paper, we investigated in more

detail the scaling properties using data from three experiments at the LHC, as well as their description using multiple partonic interactions and color reconnection in the context of PYTHIA 8 (version 8.212 tune Monash 2013) event generator.

We studied the number density in the transverse side divided by the charged-particle density in inelastic pp collisions (KNO variable). Both two quantities were calculated considering charged-particles with $p_T > 0.5$ GeV/ c . The ratio was found to increase with increasing \sqrt{s} , the trend was well described by PYTHIA 8. In particular going from pp collisions at $\sqrt{s} = 0.9$ to 7 TeV, the ratio increased by 8%–10%. In PYTHIA 8, the rate of such an increase with increasing \sqrt{s} was close to that for multiple partonic interactions. Moreover, using the limited available data, we found indications that particle production at intermediate p_T ($2 < p_T < 10$ GeV/ c) increased faster in UE than in inelastic events. Whereas at lower p_T , such an increase in both UE and inelastic events was the same within uncertainties. This effect could yield the small breaking (10%) of the KNO scaling in the particle production sensitive to UE.

The results above motivated the study of the traditional underlying-event observables considering particles within different p_T intervals. We found that color reconnection modifies the p_T spectra of unidentified charged particles,

producing a variation in the number and summed- p_T densities. In short, color reconnection enhanced the particle production at intermediate transverse momenta in regions far from the jet peaks. The modification was mass dependent, e.g., the proton-to-pion ratio as a function of p_T in the underlying-event region exhibited a flowlike response with the variation of the color reconnection strength. This behavior was very similar to what was observed in the bulk (everything outside the jet peak) region measured in heavy-ion collisions.

Our paper encourages the measurement of p_T spectra of unidentified and identified charged particles in the transverse side. The variation of such p_T spectra as a function of center-of-mass energy, p_T^{jet} (or p_T^{leading}), and system size would add key information on the origin of the heavy ionlike effects observed in pp collisions.

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